Preprint
UCRL-JC-150165

Recent Advances in the Collapse and Fragmentation of Turbulent Molecular Cloud Cores

R.I. Klein, R. Fisher, M. Krumholz, C.F. McKee

This article was submitted to
Winds, Bubbles and Explosions, September 9-13, 2002, Patzcuaro, Mexico

U.S. Department of Energy

Lawrence
Livermore
National
Laboratory

December 16, 2002

RECENT ADVANCES IN THE COLLAPSE AND FRAGMENTATION OF TURBULENT MOLECULAR CLOUD CORES

R. I. Klein,[1,2] R. Fisher,[2] M. Krumholz, [3] and C. F. McKee [1,3]

RESUMEN

El resumen será traducido al español por los editores. The formation of Giant Molecular Clouds (GMCs) sets the stage for the formation of protostellar systems by the gravitational collapse of dense regions within the GMC that fragment into smaller core components that in turn condense into stars. Developing a comprehensive theory of star formation remains one of the most elusive, and most important, goals of theoretical astrophysics. Inherent in the difficulty in attaining this goal is that the gravitational collapse depends critically upon initial conditions within the cores which only recently have been known with sufficent accuracy to permit a realistic theoretical attack on the problem. Observations of stars in the vicinity of the Sun show that binary systems are prevalent and appear to be a general outcome of the collapse and fragmentation process. Despite years of progress, theoretical studies have still not determined why binary stars occur with such frequency, or indeed, even what processes determine the transition from single stars to binaries and thence to multiple stellar systems.

One of the major goals of this research is to understand the nature of the formation of binary and multiple stellar systems with typical low mass stars 0.2 to 3 $M_{\odot}$ and the physical properties of these systems. Basic questions concerning this process remain unanswered. What determines the fraction of an unstable cloud that will fragment into protostellar objects? What determines the pattern of stellar clustering into binaries and multiple systems? Even after fragmentation occurs, we have little understanding of the subsequent collapse. Consequently, it is unclear how the mass distribution of fragments maps onto eventual stellar masses, something we must understand to explain the stellar initial mass function (IMF).

We will first discuss the development of the numerical methodology that will contribute to answering these questions. This technology consists of a 3D parallel, adaptive mesh refinement (AMR) self-gravitational, radiation-hydrodynamics code that we have developed. We will present new results for the gravitational collapse and fragmentation of marginally stable turbulent molecular cloud cores and follow the collapse of high mass fragments as they interact with the radiation of the protostars forming at their centers. We will discuss the theoretical difficulties in forming binary stars and the role of turbulence in their formation.

ABSTRACT

The formation of Giant Molecular Clouds (GMCs) sets the stage for the formation of protostellar systems by the gravitational collapse of dense regions within the GMC that fragment into smaller core components that in turn condense into stars. Developing a comprehensive theory of star formation remains one of the most elusive, and most important, goals of theoretical astrophysics. Inherent in the difficulty in attaining this goal is that the gravitational collapse depends critically upon initial conditions within the cores which only recently have been known with sufficent accuracy to permit a realistic theoretical attack on the problem. Observations of stars in the vicinity of the Sun show that binary systems are prevalent and appear to be a general outcome of the collapse and fragmentation process. Despite years of progress, theoretical studies have still not determined why binary stars occur with such frequency, or indeed, even what processes determine the transition from single stars to binaries and thence to multiple stellar systems.

One of the major goals of this research is to understand the nature of the formation of binary and multiple stellar systems with typical low mass stars 0.2 to 3 $M_{\odot}$ and the physical properties of these systems. Basic questions concerning this process remain unanswered. What determines the fraction of an unstable cloud that will fragment into protostellar objects? What determines the pattern of stellar clustering into binaries and multiple systems? Even after fragmentation occurs, we have little understanding of the subsequent collapse. Consequently, it is unclear how the mass distribution of fragments maps onto eventual stellar masses, something we must understand to explain the stellar initial mass function (IMF).

We will first discuss the development of the numerical methodology that will contribute to answering these questions. This technology consists of a 3D parallel, adaptive mesh refinement (AMR) self-gravitational, radiation-hydrodynamics code that we have developed. We will present new results for the gravitational collapse and fragmentation of marginally stable turbulent molecular cloud cores and follow the collapse of high mass fragments as they interact with the radiation of the protostars forming at their centers. We will discuss the theoretical difficulties in forming binary stars and the role of turbulence in their formation.

Key Words: **HYDRODYNAMCIS: AMR — MOLECULAR CLOUDS: COLLAPSE AND FRAGMENTATION — ISM: TURBULENT MOLECULAR CORES — STARS: LOW MASS**

1. INTRODUCTION

Most stars exist in gravitationally bound binary and low-order multiple systems. Although several mechanisms have been put forth to account for binary star formation, fragmentation has emerged as the leading mechanism for the past decade (Boss 1993; Bodenheimer et al. 2000). This point of view has been strengthened by observations that have show that the binary frequency among pre-main-sequence stars (Duchene et al. 1999) is comparable to or greater than that among nearby main-sequence stars (Duquennoy and Major 1991). This suggests that most binary stars be formed during the protostellar collapse phase which points to fragmentation as the most probable formation mechanism (Boss 2001). Moreover, the observed trend of decreasing fraction of binary and multiple systems with age strongly suggests that multiple star systems must have formed via fragmentation during the earliest stages of cloud collapse, rather than from capture of two or more stars formed individually. In order to address several central questions of multiple low mass star formation, we have developed a powerful 3D parallel, Adaptive Mesh Refinement (AMR) hydrodynamics code that includes multi fluids, radiation transport, and self-gravity.

Once fragmentation occurs, collapse proceeds largely unimpeded for low mass stars. Until very recently, the extreme variations in length scale inherent in the star formation process have made it difficult to perform accurate calculations of fragmentation and collapse, which are intrinsically three-dimensional in nature. Our development of a robust, parallel adaptive mesh refinement (AMR) self-gravitational hydrodynamics code, has resulted in our discovery of a physically motivated constraint on the resolution (the Jeans condition) that must be met to suppress artificial fragmentation (Truelove et al.1997).

Over the last few years, we have begun to investigate the properties of marginally stable, turbulent molecular cloud cores. Using turbulent simulations, we have generated models with radii, masses, density contrasts, turbulent linewidths, and projected velocity gradients consistent with observations of molecular cloud cores (Klein, Fisher & McKee, 2001, Burkert & Bodenheimer, 2000). This work represents a significant improvement over the previous theoretical work on such cores, which typically assumed a uniform spherical core with an artificially imposed perturbation (i.e. 10% $m = 2$ or white-noise density perturbations), and rigid solid-body rotation. The turbulent spectrum imposes a characteristic scale on the models, which is the scale at which the core linewidth becomes supersonic. In the past year, we have successfully integrated and tested flux-limited radiative diffusion and self-gravity into our fully three-dimensional, parallel, multifluid AMR hydrodynamics code. In § 2 we briefly describe the AMR methodology. In § 3 we present recent results of the collapse of turbulent cores with radiation transport.

2. COMPUTATIONAL METHODOLOGY/ALGORITHMS

Following the evolution of a collapsing molecular cloud as regions within it increase in density across many orders of magnitude is a formidable task. Conventional grid-based codes require that the finest-resolution gridding be applied over large volumes that may evolve to be devoid of fragments and thus not require the small zoning. Our 3-D adaptive code overcomes this problem.

First, the code employs a conservative higher-order Godunov scheme to solve the Euler equations of compressible gas dynamics using an optimized approximate Riemann solver (Toro, 1997). The algorithm is second-order accurate in both space and time for smooth flow problems, and it has a robust and accurate treatment of shocks and contact discontinuities. The code is capable of handling an arbitrary number of fluids, providing separate mass and energy equations for each.

The second major component of the code is a self-gravity solver. At each time step we solve a Poisson problem on the adaptive grid hierarchy to obtain the gravitational potential; we then apply the gradient of this potential as a source term in the momentum and energy equations (Truelove et al. 1998). A multigrid iteration scheme is used to solve the linear system of equations resulting from the discretization of the Poisson equation on a level. These level solutions are then iterated to convergence to obtain a solution for the gravitational potential on all levels. The gravity solver utilizes the same linear solver as the radiative diffusion and thermal conduction modules of our code.

The third component is an adaptive, coupled radiation hydrodynamics solver using single-frequency flux-limited diffusion. The radiation transfer module uses a split method optimized for physical conditions where radiation-gas energy exchange by emission/absorption dominates the work done by the

[1]Univ. of Cal., Berkeley, Dept. of Astronomy.
[2]Univ, of Cal., Lawrence Livermore National Lab.
[3]Univ. of Cal., Berkeley, Dept. of Physics.

radiation field on the gas. First, the code solves a fully impilicit system consisting of the emission/absorption and diffusion parts of the radiation and gas energy equations (Howell & Greenough 1999). It uses a Newton-Raphson iteration method, with an adaptive parallel multigrid method to find provisional solutions in each loop of the iteration. Once the implicit system reaches convergence, the algorithm updates the gas and radiation states using explicit forms of the radiation pressure force, work and advection terms.

These solvers for hydrodynamics, self-gravity, and radiative transfer are coupled together within the adaptive mesh refinement infrastructure of our code. The adaptive mesh refinement scheme employs an automatic, dynamic regridding strategy based on an underlying rectangular discretization of the spatial domain (Berger & Oliger 1984, Berger & Colella 1989; Bell et al. 1994). Special difference equations guarantee conservation across the interfaces between grids at different levels of resolution. The overall algorithm conserves total energy, mass, and momentum because the time-step update applied at each grid at each level of refinement and the couplings at the interfaces between grids at different levels are all in conservation form.

3. COLLAPSE AND FRAGMENTATION OF TURBULENT CORE

Binary stars have a wide range of periods, ranging from less than a day to more than 10^6 yr (Bodenheimer et al 2000). The median period is 180 yr; for a total binary mass of 1 $M_\odot$, the corresponding separation is about 30 AU $= 4.5 \times 10^{14}$ cm.

It is crucial that the initial models which one uses faithfully describe those present in nature. High-resolution observations of molecular cloud cores (eg, Motte and Andre 2001) indicate that the mean column density of pre-stellar molecular cloud cores is close to that of a centrally condensed isothermal sphere supported primarily by thermal pressure. Moreover, observations of linewidths in star-forming regions indicate that the non-thermal linewidths are typically transonic on the scale of cores, and obey a power law linewidth-size relation (Larson 1981). In the past year, we have, for the first time, generated self-consistent, initial conditions for cores in virial balance between gravity and thermal and turbulent pressures, which incorporate density fluctuations in addition to those present in the velocity field, and which match these key known observational properties of cores. In contrast, nearly all calculations which appear in the literature deal with initial cores unrealistically far from equilibrium (e.g. Boss & Bodenheimer 1979, Boss 1991, Burkert & Bodenheimer 1993), without any turbulent support, leading to highly supersonic collapse velocities, and artificially symmetric collapses.

3.1. *Initial Conditions*

Truly accurate simulations for collapse must begin from realistic initial conditions, with self-consistent turbulence in both velocity and density. To generate such initial conditions, we would ideally start from a large turbulent box simulation of a cloud and allow the cloud to form dense subregions that become the molecular cloud cores whose properties are well studied with high-resolution observations. These turbulent cores would then be evolved though the first gravitational collapse and fragmentation phase to protostellar formation and the subsequent distribution of single, binary and multiple stars would be analysed. As a preliminary step to investigate such realistic initial conditions, we start instead with a smooth Bonnor-Ebert sphere and perturb only the velocity field with Gaussian perturbations on large scales; we adjust the energy injection rate of the perturbation to achieve the desired turbulent Mach number. This naturally produces the turbulent power spectrum $p(k) \propto k^{-4}$ predicted by theory and by Larson's law (Larson 1981). After a few sound crossing times, we take the resulting object as our initial condition for a collapse calculation of a molecular cloud core. We simulate observations of these cores to determine: the axis ratio (Myers et al 1991); β, the ratio of rotational kinetic to gravitational potential energy (Goodman et al 1993); and γ, the exponent of the single-object linewidth-size relation (MacLow & Ossenkopf 2002). We find excellent agreement between the simulated cores and observations. We have found (to be published elsewhere) that if we are simulating a barotropic cloud that obeys Larson's laws, and if the initial thermal temperature is fixed, then the initial conditions for a typical case are determined by a single number $\mathcal{M}$, the turbulent Mach number in the cloud. Thus our initial cores can be thought of as a subregion of the larger turbulent cloud, characterised in scale by the Mach number of the gas in the sub region. We are currently performing more self-consistent detailed collapse simulations of full turbulent clouds with perturbations affecting both the velocity and density fields and this will be reported elsewhere.

3.1.1. *Preliminary Results*

We have begun simulating turbulent low-mass cores, including the effects of radiative transfer in the flux-limited diffusion approximation. To the best of our knowledge, these are the first astrophysical simulations in star formation incorporating flux-limited radiation diffusion on an adaptive mesh. We begin with an initial $8M_{\odot}$ core with a turbulent Mach number of $\mathcal{M} = 3$. In Fig. 1, we view the log of the column density of the core at t $=3.84 \times 10^{12} sec$ corresponding to 0.086 edge free fall times after the start of collapse. Note the formation of a binary embedded in a highly irregular core with an orbital separation of 3700 AU. A similar calculation using a barotropic approximation for the equation of state produces almost identical results. At this time the core structure is still optically thin and we would not expect any significant results of the radiation on the fragmentation. Fig. 2 shows the binary at t $=4.13 \times 10^{12} sec$. The binary has a separation distance of 2800 AU. Each member of the binary appears to be surrounded by a disk with one component of the binary showing a 2 arm spiral. The binary appears to form inside the structure of a filament in the cloud core. Some differnces are noted with a pure barotropic calcution in which the binary has a somewhat smaller separation of 2400 AU. Fig. 3 shows the full scale of the core with the binary present at t $=4.63 \times 10^{12} sec$ and a blow up of the binary star system with an orbital separation of $\simeq$ 836 AU. The binary is formed within a filamentary structure and at this time is too close to adequately resolve. By the endpoint of the simulation, roughly 20% of the mass of the original core had been accreted. An interesting result of this particular model is that the filamentary structure of the turbulent cloud remained optically thin throughout the duration of the simulation. It remains to be seen which models build up optically thick turbulent density structures, and precisely what impact radiative transfer has on the fragmentation process in general.

REFERENCES

Bell, J., Berger, M., Saltzman, J., and Welcome, M. 1994, SIAM J. Sc. Comp, 15, 127

Berger, M. J. and Colella, P. 1989, J. Comput. Phys., 82, 64

Berger, M. J. and Oliger, J. 1984, J. Comput. Phys., 53, 484

Bodenheimer, P., Burkert, A., Klein, R. I., & Boss, A. P. 2000, in *Protostars and Planets IV*, ed. V. Mannings, A. P. Boss, & S. Russell (Tucson: University of Arizona Press), p. 675.

Boss, A. P. 1991, Nature, 351, 298

Boss, A P. 1993,

Boss, A., and Bodenheimer, P., 1979, ApJ, 234, 289

Burkert, A. and Bodenhimer, P., 2000, ApJ, submitted

Duchene, G., Bouvier, J., & Simon T., 1999, A&A. 343, 831

Goodman, A. A., Benson, P. J., Fuller, G. A., & Myers, P. C. 1993, ApJ, 406, 528

Howell, L.H. and Greenough, J.A., Block-structured Adaptive Mesh Refinement Algorithm for Diffusion Radiation, UCRL-JC-133094, 1999

Klein, R. I., Fisher, R. T., McKee, C. F., 2001, *IAU 200 International Conference on the Formation of Binary Stars*, eds. Zinnecker, H., & Matthieu, R

Larson, R. 1981, MNRAS, 194, 809

Myers, P. C., Fuller, G. A., Goodman, A. A., & Benson, P. J. 1991, ApJ, 376, 561

Motte, F. & André, P. 2001, A&A, 365, 440

Ossenkopf, V. & MacLow, M.-M. 2002, A&A, 390, 307

Toro, E. 1997, *Riemann solvers and numerical methods for fluid dynamics : a practical introduction*, Berlin

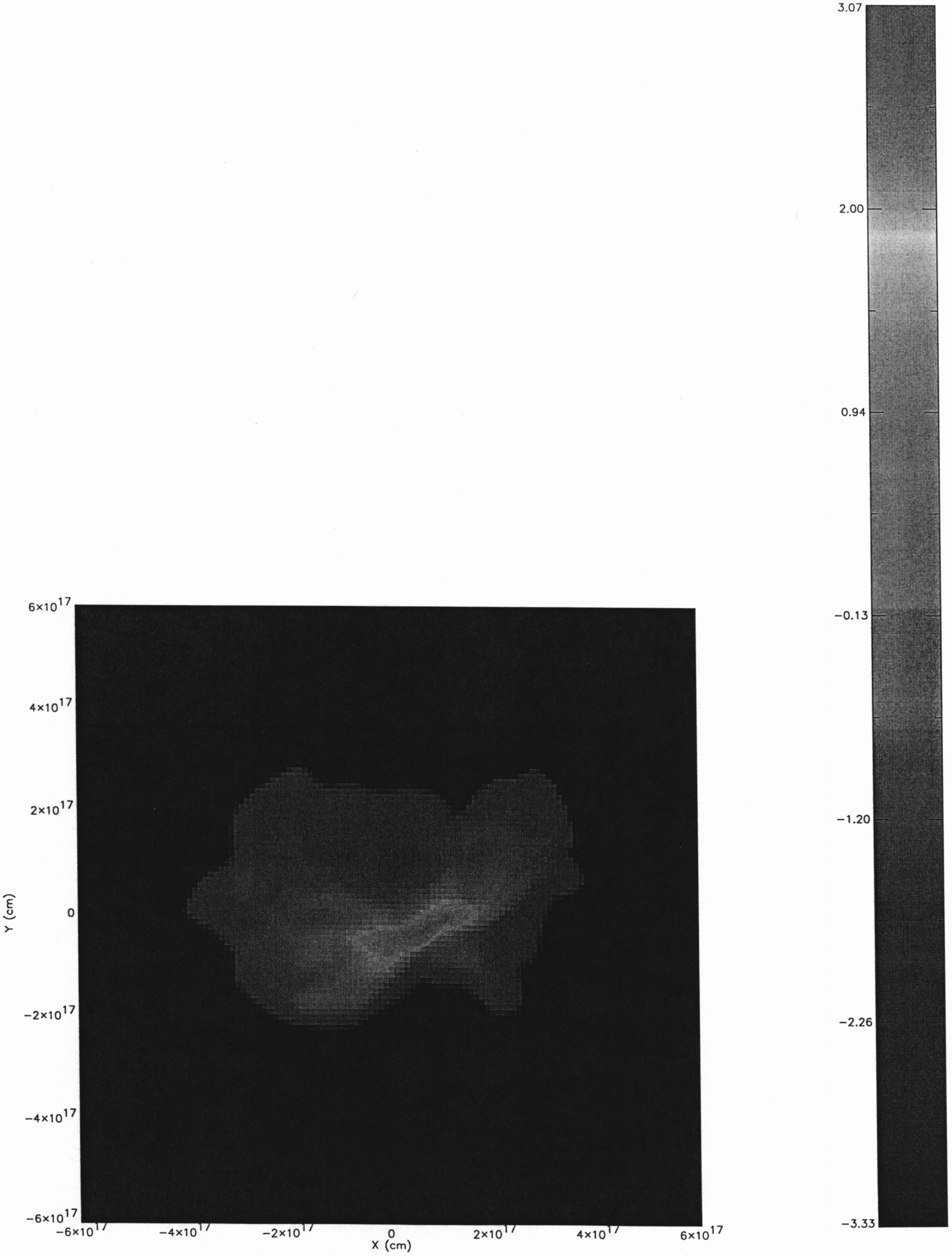
Truelove, J.K., Klein, R.I., McKee, C.F., Holliman, J.H., Howell, L. H., Greenough, J.A., and Woods, D. T., 1997. ApJ, 489, L179

Truelove, J.K., Klein, R.I., McKee, C.F., Holliman, J.H., Howell, L.H., Greenough, J.A., 1998. ApJ, 495, 821

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

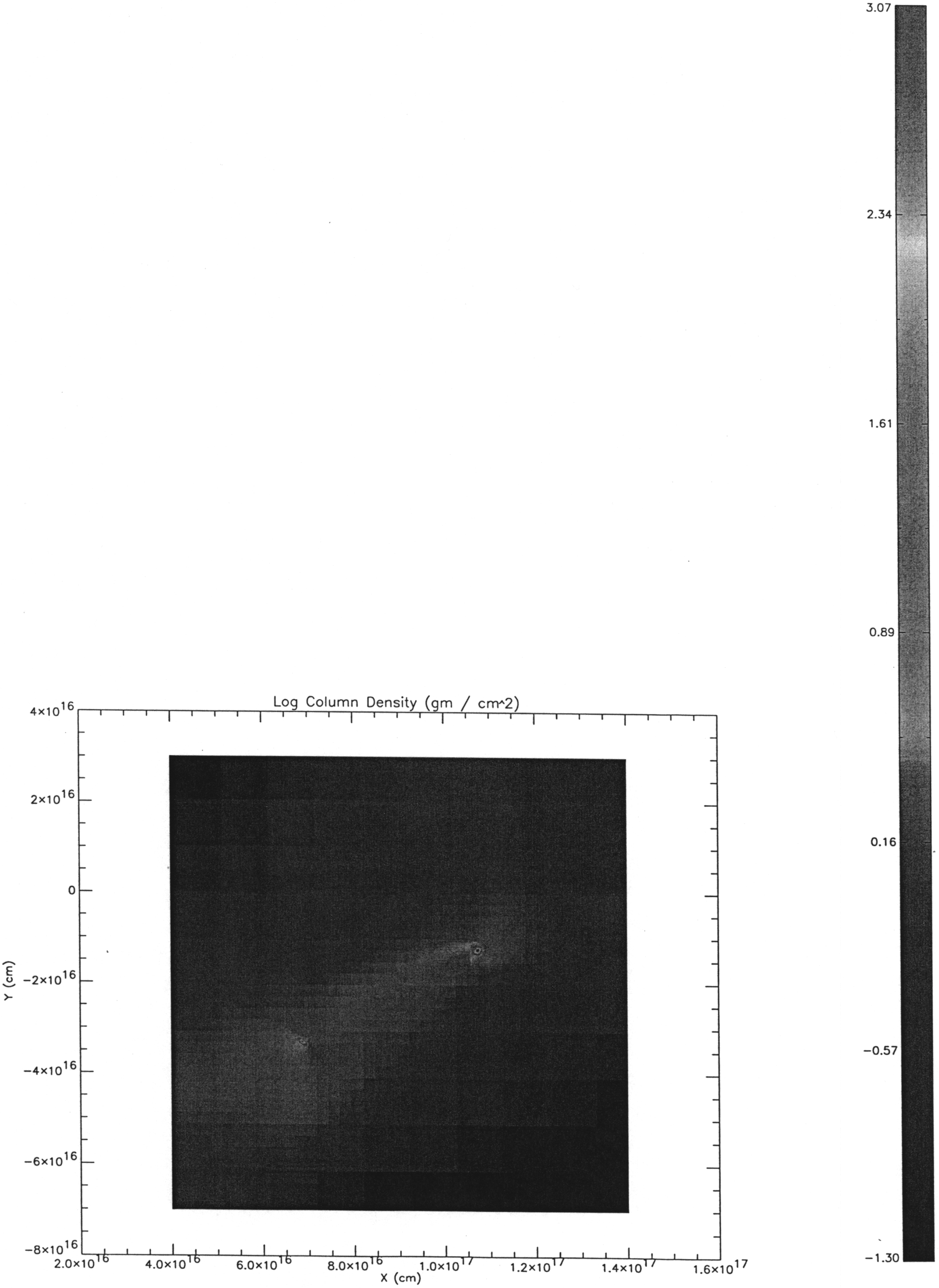
Richard I. Klein and Christopher F. McKee: Univ. of California, Berkeley, Dept, of Astronomy, 601 Campbell Hall, Berkeley, Cal. 94720 (rklein@astron.berkeley.edu, cmckee@astron.berkeley.edu).
Richard I. Klein and Robert Fisher: Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California, 94550 (rklein@astron.berkeley.edu, rfisher@llnl.gov).
Mark Krumholz and Christopher F. McKee: Univ. of California, Berkeley, Dept. of Physics, Berkeley, Cal. 94720 (mkrumholz@astron.berkeley.edu, cmckee@astron.berkeley.edu).

Figure 1



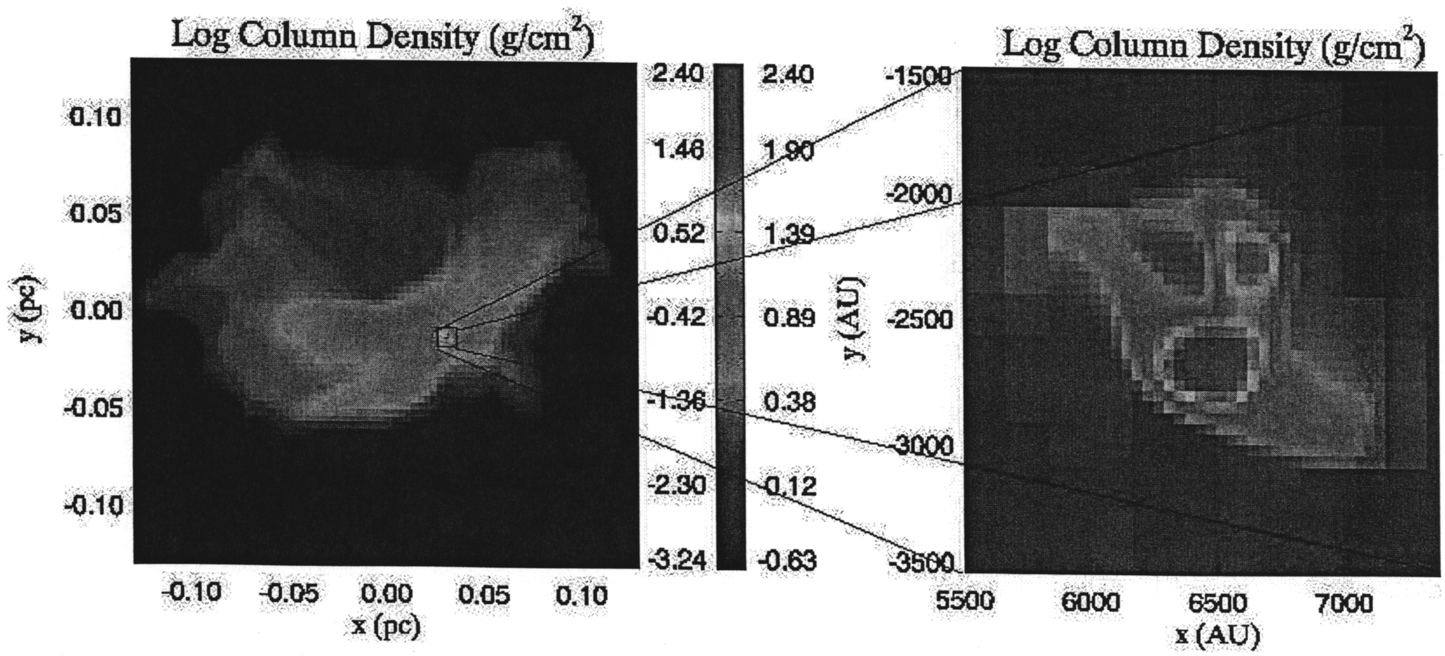
6×10^17
4×10^17
2×10^17
0
−2×10^17
−4×10^17
−6×10^17
Y (cm)
−6×10^17
−4×10^17
−2×10^17
0
2×10^17
4×10^17
6×10^17
X (cm)
3.07
2.00
0.94
−0.13
−1.20
−2.26
−3.33

Figure 2



Log Column Density (gm / cm^2)
4×10^16
2×10^16
0
−2×10^16
−4×10^16
−6×10^16
−8×10^16
Y (cm)
2.0×10^16
4.0×10^16
6.0×10^16
8.0×10^16
1.0×10^17
1.2×10^17
1.4×10^17
1.6×10^17
X (cm)
3.07
2.34
1.61
0.89
0.16
−0.57
−1.30

Figure 3



Log Column Density (g/cm^2)
0.10
0.05
0.00
-0.05
-0.10
y (pc)
-0.10
-0.05
0.00
0.05
0.10
x (pc)
2.40
1.46
0.52
-0.42
-1.36
-2.30
-3.24
2.40
1.90
1.39
0.89
0.38
-0.12
-0.63
Log Column Density (g/cm^2)
-1500
-2000
-2500
-3000
-3500
y (AU)
5500
6000
6500
7000
x (AU)